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Evaluating the level and nature of sustainable development for a geothermal power plant

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ABSTRACT

The paper provides for an evaluation of the potential level and nature of sustainable development of the Sabalan geothermal power plant in NW Iran, to be operational in 2011. The paper achieves this by applying a mathematical model of sustainable development developed by the author (re: Phillips [17,18]), in respect to the Environmental Impact Assessment (EIA) conducted by Yousefi et al. [13] using the Rapid Impact Assessment Matrix (RIAM) methodology (re: Pastakia [15]; Pastakia and Jensen [16]). Using a model application methodology developed for the RIAM, the results indicated that the nature of sustainable development for Sabalan was considered to be very weak ($S = 0.063$). This was due to the imbalance between negative environmental impacts and positive socio-economic impacts deriving from the project. Further, when placed into context with a similar set of results obtained from the EIA of the Tuzla geothermal power plant by Baba [35] also using the RIAM methodology, then the similarities between the results obtained raises some legimate questions as to the sustainable development credentials of geothermal power production.

Contents

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1. Introduction

In recent years, the emphasis towards renewable sources of energy production has intensified. There is now a concerted international effort to develop and utilise carbon-free sources of energy in order to combat the potential causes of climate change.

Energy has always an important role in the development of human society [1], as it is essential to economic and social development, as well as improved quality of life in all countries [2,3]. The use of vast quantities of fossil fuels since the Industrial Revolution for energy production has resulted in the emission of greenhouse gases, which is strongly believed to be the cause of climate change.

Climate change is one of the most profound challenges facing the world [3], with serious consequences for social and economic infrastructure as well as the natural environment [2]. Preventing the inferred anthropogenic influences would require changes in energy production, distribution and consumption. With the increasing awareness of the detrimental effects of fossil fuel use upon the environment, there is now global interest in renewable energy sources. For it to be considered as renewable, it has to be: (1) carbon-neutral; and (2) derived from natural, mechanical, thermal and growth processes that repeat themselves within our lifetime [4]. Potential renewable sources of energy are well documented in the literature: wind, tidal, wave solar, hydro, bioenergy and geothermal. Geothermal energy is considered to be one of the most promising [5], as it provides a clean, reliable and environmental benign source of energy [5,6]. It is also considered to be consistent with the ideals of sustainable development in that it seeks environmental protection and economic development [2,7–12]. However, there is evidence of adverse environmental impacts [13,14] from geothermal energy production This is due to the fact that the heated fluid of vapour trapped beneath the Earth's crust can vary dependent upon locality, geology, depth, pressure, temperature and chemical composition [14]. Subsequently, this can result in different environmental impacts occurring from field to field.

This paper will examine the case study of the Sabalan geothermal power plant as assessed by Yousefi et al. [13], using the Rapid Impact Assessment Matrix (RIAM) [15,16]. This is a semi-quantitative methodology of Environmental Impact Assessment (EIA) for determining and analysing impacts of environmental and anthropogenic components of the project. Utilising the assessment data obtained by Yousefi et al. [13], the paper will determine the level and nature of sustainable development of the plant (if appropriate). This will be achieved by the application of a mathematical model of sustainable development to the results of the RIAM analysis. The model, as detailed in Phillips [17,18], describes the nature of the relationship between the environment and humans that constitutes sustainable development, and the conditions necessary for it to occur. The application of the model was initially developed for use in respect to two quantitatively based methodologies of EIA: RIAM and the Battelle Environmental Evaluation System (BEES) [19].

2. Literature review

2.1. Geothermal energy

2.1.1. Overview

Geothermal energy is heat stored in the Earth's crust within the rocks and fluids. It is this heat which provides the mode for electricity generation or for direct use. The temperature within the Earth increases depth, and consequently, the heat resources can be used through drilling wells and piping steam or hot water to the surface [20,4].

There are two fundamental approaches in utilising geothermal energy:

(1) *Hydrogeothermal*: Hot water reservoirs tapped underground. This water can be then used for heating and where temperature is high enough, used for electricity generation [2].
(2) *Hot dry rock*: Water pumped into a fundamental hot plutonic rock under high pressure. The water heats up underground and return via a second borehole. This allows the heated water to be used for electricity and water [2].

Geothermal energy is being strongly considered as it is potentially inexhaustible [2]. However, it only accounts for approximately 0.5% of the global primary energy supply [21,22]. Hepbasil and Ozgener [23] indicate that the potential global geothermal energy generation is approximately 1089 billion kWh/yr. Therefore, geothermal energy has the potential to contribute significantly sustainable energy globally [23]. However, geothermal energy does entail some environmental impacts.

2.1.2. Environmental impact of geothermal energy

The potential environmental impacts deriving from geothermal energy production have been detailed in the literature. These can be summarised as follows:

- *Air pollution*: Steam from major geothermal fluids contain between 1.0 and 50 g/kg of non-condensable gases emitted. These gases are CO_2, H_2S, NH_3, CH_4, N_2 and H_2. CO_2 emissions range from 13 to 380 g/kWh, compared to 453 g/kWh for natural gas, 906 g/kWh for oil, and 1042 g/kWh for coal [25]. However, H_2S is of some concern, given its role in the formation of acid rain. Emissions of H_2S are generally in the region of 0.5–6.8 g/kWh [24]. Further, geothermal steam may contain as well trace mercury (Hg), boron vapours (B), and radon (Rn). Gases of B, NH_3, and to a lesser extent Hg are leached from the atmosphere by precipitation causing contamination to the soil and vegetation [24]. Boron is of particular concern, with serious consequences for vegetation, surface waters and aquatic organisms [24]. Emissions of Hg are comparable to those of coal-fired power stations (45–900 mg/kWh) [24]. Emissions of Rn in steam are at concentrations of 3700–78,000 Bq/kWh [26]. There is little evidence however that levels of Rn significantly exceed background levels in respect to geothermal steam emissions.

- *Water pollution*: The extraction and use of water in geothermal energy raises questions as to potential environmental issues. This is in relation to either water quality, water availability or use of water resources [14]. Whilst water pollution can be mitigated for, the following potential incidents can occur, as noted by Brophy [14]:
  - Accidents that result in spillages of geothermal fluids onto the surface.
  - Spillages of toxic or hazardous substances used during exploration, construction or production phases.
  - Failure of drainage structures for storm run-off or other surface water flows.
  - Leakages from surface storage impoundments, e.g. drilling slumps or holding ponds.

The type of geothermal power plant can determine the nature of the pollution emitted. In the case of vapour-dominated reservoirs, then the water and condensate would contain a range of toxic chemicals in suspension and solution: As, Hg, Pb, Zn, B and S, along with carbonates, silica, sulphates and chlorates [24]. In the case of water dominated and hot water reservoirs, water and steam (if present) are separated on the surface. The steam is used for electricity generation whilst the water disposed of is equivalent to as much as 70 kg/kWh [24]. The disposed water may contain significant quantities of salts, which can exceed 300 g/kg of the extracted fluid [24].

- *Land issues*: Landslides and soil erosion are potential hazards, particularly in areas where there are steep slopes and high precipitation [14]. Ground subsidence has been observed in some geothermal areas due to fluid removal over an extended period of time [14]. However, induced seism city in geothermal areas is in issue. This is due to many geothermal zones are located in geologically unstable areas [24,14]. Therefore, volcanic activity, deep earthquakes and higher temperature heat flows are characteristic of such areas [24]. Consequently, such risks need to be fully evaluated before development occurs in these areas [24].
- *Noise*: Whilst most geothermal facilities are built away from major urban areas, levels still are relatively low [14]. Newly drilled wells or during maintenance have a noise level of 90–122 dB at free discharge, and 75–90 dB using silencers [27]. However, significant nuisance may be created by vehicular activity, construction activities, unabated steam releases, and certain drilling operation [14].
- *Ecology*: Geothermal energy may have impacts upon terrestrial, riparian and aquatic habitats [14]. This would be of significance where loss of habitat threatens rare or endangered species due to construction of facilities such as roads, drilling pads, pipelines and power plants [14].

2.2. Sustainable development and geothermal energy

Since the 1970s, the increasing concern of global environmental degradation led to the acceptance that there needed to be a balance between economic growth and environmental preservation—the concept of sustainable development [4]. Sustainable development however does not make the world 'ready' for future generations, but rather lays the foundations for which the future world can be built upon [10]. However, in recent years, sustainable development has become a popular buzzword in discussing resource use and environmental policy [8]. This is somewhat of concern, given the potential catastrophic issues facing humanity and the planet.

The World Summit on Sustainable Development (WSSD) in Johannesburg in 2002 committed itself to: "encourage and promote the development of renewable energy source to accelerate the shift towards sustainable consumption and production" [28]. This, as Omer [11] states, was aimed at breaking the link between resource use and productivity. This is achieved by the following:

1. Ensuring that economic growth does not cause environmental pollution.
2. Improve resource efficiency.
3. Examine the entire life-cycle of the product.
4. Enabling consumers to get more information on products and services.
5. Examine how the role of taxes, voluntary agreements, subsidies, regulation and information campaigns, can best be used to stimulate innovation and investment for cleaner technology.

This is based on the recognition by society of the importance of intelligent energy use, with the requirement that energy services are as clean and efficient as possible [8]. Consequently, sustainable development demands sustainable energy supply [9]. This supply must be cost-efficient, reliable, and environmental friendly [9,10]. However, the development of sustainable energy systems requires an understanding of the potential environmental and human consequences (positive and negative). To the end, there has been an increasing attention in the recent development of the concept of sustainability science [11].

2.3. Sustainability science

There has been an increasing attention in the recent development of the concept of sustainability science, which seeks to understand the interactions between nature and society [11]. Sustainable development focuses on the role and use of science in the prudent management of the environment, and for future human development [8]. Consequently, it recognises that knowledge should be applied in supporting the goals of sustainable development through the use of scientific assessment of the current conditions and future prospects for the Earth system [8].

"Sustainability science has emerged over the last two decades as a vibrant field of research and innovation" [29]. The specific questions that sustainability science attempt to address are defined by Kates et al. [30]:

1. How can those dynamic interactions be better incorporated into emerging models and conceptualisations that integrate the Earth system, social development, and sustainability?
2. How are long-term trends in environment and development reshaping nature-society interactions?
3. What factors determine the limits of resilience and sources of vulnerability for such interactive systems?
4. What systems of incentive structures can most effectively improve social capacity to guide interactions between nature and society towards more sustainable trajectories?
5. How can science and technology be more effectively harnessed to address sustainability goals?

Therefore, as Clark [29] goes onto to state: "from its core focus on advancing understanding of coupled human-environment systems, sustainability science has reached out with focused problem-solving efforts targeted to urgent human needs". However, understanding such coupled systems are "made all the more unpredictable by both our interest in what goes on in particular places and by our active, reflective engagement in the system whose behaviour we are trying to predict" [31].

Sustainability science as a consequence is "most usefully thought of as neither 'basic' nor 'applied' research" [29]. Instead,

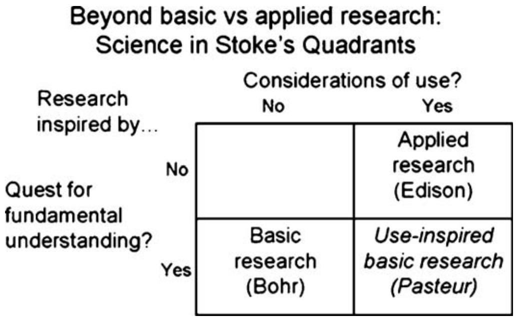

Fig. 1. Research characterised by the motivations that inspire it (Clark [31], Fig. 1; redrawn from Stokes [32]).

with reference to Fig. 1, it is focussed upon the "use-inspired basic research" that Stokes [32] characterised as 'Pasteur's Quadrant' of the modern science and technology enterprise. The field of sustainability science has reached beyond this, to embracing appropriate research in the "blue-sky theorizing of 'Bohr's Quadrant' and pragmatic problem solving of 'Edison's Quadrant'" [29]. This approach as a result means that it assists the pursuit for "advancing both useful knowledge and informed action by creating a dynamic bridge between the two" [29].

3. Methodology

3.1. The Rapid Impact Assessment Matrix

3.1.1. Overview

The Rapid Impact Assessment Matrix (RIAM) method [15,16] is based on a standard definition of the important assessment criteria. By this, semi-quantitative valuation for each of these criteria can be collated, providing an accurate and independent score for each condition [16].

The impacts of project activities are evaluated against the environmental components, and using the defined criteria for each component, a score is determined. This score a measure of the impact expected from the component [15,16].

The important assessment criteria fall into two groups:

- *Criteria A* that denotes the importance to the condition, and which can individually change the score obtained.
- *Criteria B* that determines the impact value to the situation, but individually should not be capable of changing the score obtained.

The value determined to each of these groups of criteria is determined by the use of a series of simple formulae. These formulae allow the scores for the individual components to be determined on a defined basis [15,16].

The scoring system involves a simple produce to determine the overall environmental score (ES) for each criteria being assessed, as seen below:

$(a1) \times (a2) = aT(b1) + (b2) + (b3) = bT$

$(aT) \times (bT) = ES$

where $(a1)$ and $(a2)$ are the individual criteria scores for group (A); $(b1)$ to $(b3)$ are the individual criteria scores for group (B); aT is the result of multiplication of all (A) scores; bT is the result of summation of all (B) scores; ES is the assessment score for the condition.

Positive and negative impacts are represented by using scales that pass from negative to positive values through zero for the group (A) criteria. Zero consequently represents 'no-change' or 'no-importance' value. The use of zero in group (A) criteria allows for the ability to use a single criterion to isolate conditions which indicate no change or are unimportant to the analysis [16].

A value of zero avoided in the group (B) criteria because if all group (B) criteria score zero, the final result of the ES will also be zero. This condition may occur even where the group (A) criteria show a condition of importance that should be recognised [16]. In order to avoid this situation, scales for group (B) criteria use '1'as the 'no-change/no-importance' score.

3.1.2. Assessment criteria

The criteria needs to be defined for both groups, as well as based upon the fundamental conditions which may be influenced by change, as opposed to being related to a particular individual project. Whilst it is possible to define a number of criteria, two principles must always be satisfied [15,16]:

1. The universality of the criterion, to allow it to be used in different EIAs.
2. The value of the criterion, which determines whether it should be treated as a Group (A) or Group (B) condition.

Consequently, only five criteria are used in the RIAM. Nevertheless, these five criteria represent the most important fundamental assessment conditions for all EIAs, and satisfy the principles set out above [15,16]. These criteria, together with their appropriate judgement scores are defined as follows:

3.1.2.1. Group (A) criteria. Importance of condition (a1): This is a measure of the condition's importance. It is assessed against the spatial boundaries or human interests that it affects [15]. The scales are defined as:

4—important to national/international interests.
3—important to regional/national interests.
2—important to areas immediately outside the local condition.
1—important only to the local condition.
0—no importance.

Magnitude of change/effect (a2): Magnitude is defined as a measure of the scale of benefit/disbenefit of an impact or a condition [15]:

+3—major positive benefit.
+2—significant improvement in status quo.
+1—improvement in status quo.
0—no change/status quo.
−1—negative change to status quo.
−2—significant negative disbenefit or change.
−3—major disbenefit or change.

3.1.2.2. Group (B) criteria. Permanence (b1): This determines whether a condition is temporary or permanent. This therefore should be viewed only as a measure of the temporal status of the condition [15]. The scoring for each condition is as follows:

1 No change/not applicable.
2 Temporary.
3 Permanent.

Reversibility (b2): This defines whether or not the condition can be changed. This consequently reflects the measure of the control over the effect of the condition. It should not it any way is related or confused with permanence [15]. The scoring for each condition is as follows:

Table 1
An example of the results generated for the RIAM assessment of environmental impacts of option no. 3 (relocation of landfill) in respect to Russeifa Landfill, Jordan, as conducted by El-Naqa [33].

	Components	ES	RB	A1	A2	B1	B2	B3
Physical and chemical components (PC)								
PC1	Odours and gaseous emissions	−6	−A	1	−1	2	2	2
PC2	Groundwater pollution	−6	−A	1	−1	2	2	2
PC3	Dust	0	N	1	0	2	3	2
PC4	Noise	0	N	1	0	2	2	2
PC5	Air Pollution	−7	−A	1	−1	2	3	2
PC6	Impacts from increased industrial activity	−12	−B	2	−1	2	2	2
Biological and ecological components (BE)								
BE1	Impacts on biota	−6	−A	1	−1	2	2	2
BE2	Damage of habitats	−12	−B	1	−2	2	2	2
BE3	Aesthetics impact	−6	−A	1	−1	2	2	2
BE4	Littering	−6	−A	1	−1	2	2	2
Sociological and cultural components (SC)								
SC1	Public acceptability	−6	−A	1	−1	2	2	2
SC2	Work opportunity	12	B	2	1	2	2	2
SC3	Public health	−6	−A	1	−1	2	2	2
SC4	Impact on housing	−6	−A	1	−1	2	2	2
SC5	Population growth	−5	−A	1	−1	2	1	2
SC6	Public safety	−12	−B	2	−1	2	2	2
Economical and operational components (EO)								
EO1	Operation and maintainance	−5	−A	1	−1	2	1	2
EO2	Recycling	36	D	2	3	2	2	2
EO3	Traffic	−6	−A	1	−1	2	2	2
EO4	Property value loss	−6	−A	1	−1	2	2	2
EO5	Health costs to community	−6	−A	1	−1	2	2	2

1 No change/not applicable.
2 Reversible.
3 Irreversible.

Cumulative (b3): This is a measure of the nature of the effect. Whether the effect will have a single direct impact, or whether there will be a cumulative effect over time, or a synergistic effect with other conditions [15]. This criterion is a mechanism for evaluating the sustainability of a condition. It should not therefore be confused with a permanent/irreversible situation [15].

1 No change/not applicable.
2 Non-cumulative/single.
3 Cumulative/synergistic.

It is possible to change the cumulative component to one of synergism, if the condition warrens consideration of additive affects [15].

3.1.3. Environmental components

The RIAM requires specific assessment components to be defined through a process of scoping; and these environmental components fall into one of four categories, which are defined as follows [15,16]:

Physical/chemical (PC): This covers all physical and chemical aspects of the environment, including finite (non-biological) natural resources, and degradation of the physical environment by pollution.

Biological/ecological (BE): This covers all biological aspects of the environment, including renewable natural resources, conservation of biodiversity, species interactions, and pollution of the biosphere.

Sociological/cultural (SC): This covers all human aspects of the environment, including social issues affecting individuals and communities; together with cultural aspects, including conservation of heritage, and human development.

Economic/operational (EO): This seeks identify qualitatively the economic consequences of environmental change, both temporary and permanent, as well as the complexities of project management within the context of the project activities.

Using these four categories can be, in itself, provide a capable tool for EIA. However, each category can be further sub-divided to identify specific environmental components in order to demonstrate the possible impacts [16]. Consequently, the degree of sensitivity and detail of the system can be controlled in the selection and definition process for these environmental components [15].

3.1.4. Evaluation and presentation

To use the evaluation system described, a matrix is produced for each project option [15] (see Table 1 for an example). The matrix comprises of cells showing the criteria used, set against each defined component, whereby within each cell, the individual criteria scores are set down [15]. From the formulae given for each ES number is calculated and recorded. Once the ES score is set into a range band (re: Table 2), which is $-108 \leq ES \leq 108$. The relevant scores can then be shown individually or grouped according to

Table 2
Range bands used for RIAM, as stated by Pastakia [15].

Environmental score	Range bands	Description of range band
+72 to +108	+E	Major positive change/impacts
+36 to 71	+D	Significant positive change/impacts
+19 to +35	+C	Moderately positive change/impacts
+10 to +18	+B	Positive change/impacts
+1 to +9	+A	Slightly positive change/impacts
0	N	No change/status quo/not applicable
−1 to −9	−A	Slightly negative change/impacts
−10 to −18	−B	Negative change/impacts
−19 to −35	−C	Moderately negative change/impacts
−36 to −71	−D	Significant negative change/impacts
−72 to −108	−E	Major negative change/impacts

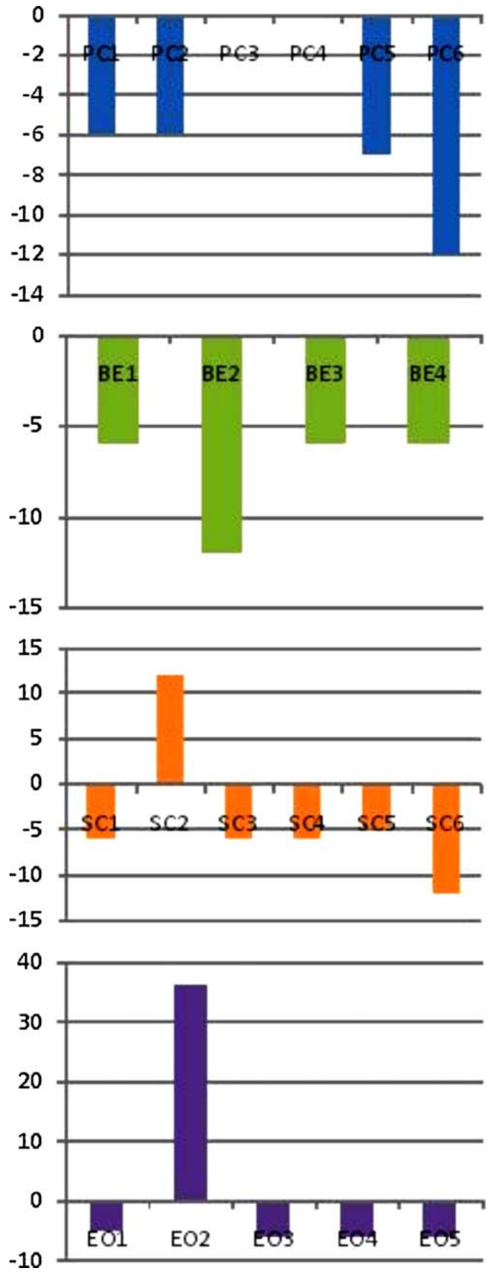

Fig. 2. Graphical representation for the individual categories of the RIAM assessment of environmental impacts of option no.3 (relocation of landfill) in respect to Russeifa Landfill, Jordan, as conducted by El-Naqa [33].

component type and presented in whatever graphical (Fig. 2) or numeric form required [15].

3.2. Model application

3.2.1. Overview

This paper is based on research conducted on two issues: (1) the conceptualisation and determination of sustainable development in the form of a mathematical model, which describes the fundamental parameters and dynamics of sustainable development; and (2) the model's initial application to two quantitative-based methodologies of Environmental Impact Assessment, for the purpose of evaluating the level and nature of sustainable development of proposed or current projects.

These points have been addressed by Phillips (see [17,18]), and which this research has been extended to the question of the level and nature of sustainable development concerning the construction and operation of the Sabalan geothermal power plant. This was due to the apparent high regard for such projects in achieving sustainable development. One of the key challenges faced during the research which the determination to how to apply the model (re: [17,18]) to the RIAM methodology, which will be highlighted further.

3.2.2. Determination of model application procedure

The determination of how to apply the model involved, to some degree, a trial and error approach [17,18]. This meant working out precisely how to use the expressions to calculate sustainable development by repeatedly applying the EIA data, and referring back to the obtained value of sustainable development (the *S*-value) to the original results and conclusions reached [17,18]. By this approach, it meant determining whether or not the obtained value of sustainable development was reflective in the results and conclusions reached in the EIA [17,18].

When initially using the RIAM methodology, the model could not be applied immediately [17]. This was due to the use of negative values in the RIAM in referring to the extent of negative impacts upon the environment, and the potential for a final negative Environment Score (ES) for each assessment parameters [17]. This was because the model states that $S = E - H_{NI}$ for the calculation of the level of sustainable development (if appropriate) [17]. The problem this raised was that if a negative final *ES* was obtained when calculating the determined values of *E* (the environment) or H_{NI} (Human Needs and Interests), then the negative value would create a potential issue regarding the calculation of *S* (sustainable development) [17]. For example, if a high negative value of H_{NI} was subtracted from a low negative value of *E*, this would result in a positive *S*-value (obtained value of sustainable development), which would be obviously wrong [17].

The solution for this problem was very straightforward [17]. As the *ES* range for each condition was $-108 \leq ES \leq 108$, it seemed reasonable to alter the potential range so that it started from zero [17]. This would conform to the value range of the model of $0 \leq x \leq 1$ [17]. Consequently, by adding 108 to all of the *ES* values, and therefore changing the potential range to $0 \leq ES \leq 216$, this kept the nature and extent of the impact indicated upon the parameters stated [17]. As a result, this meant it was possible to calculate the potential level and nature of sustainable development using the model for the RIAM methodology [17].

3.3. Model application methodology

3.3.1. Glossary of terms

The terminology for the model application methodology to be detailed in Fig. 2 is as follows:

S = sustainable development (environmental)
S_{Ec} = sustainable development (ecological)
E = the environment
E_B = biological environment/ecology
H_{NI} = human needs and interests
A = atmosphere
B = biosphere
H = hydrosphere
L = lithosphere

3.3.2. Model application—Rapid Impact Assessment Matrix (RIAM)

The model application process used for evaluating the level and nature of sustainable development using the RIAM approach is provided in Fig. 3. This was developed in order to simplify and illustrate clearly and concisely the methodology for applying the model.

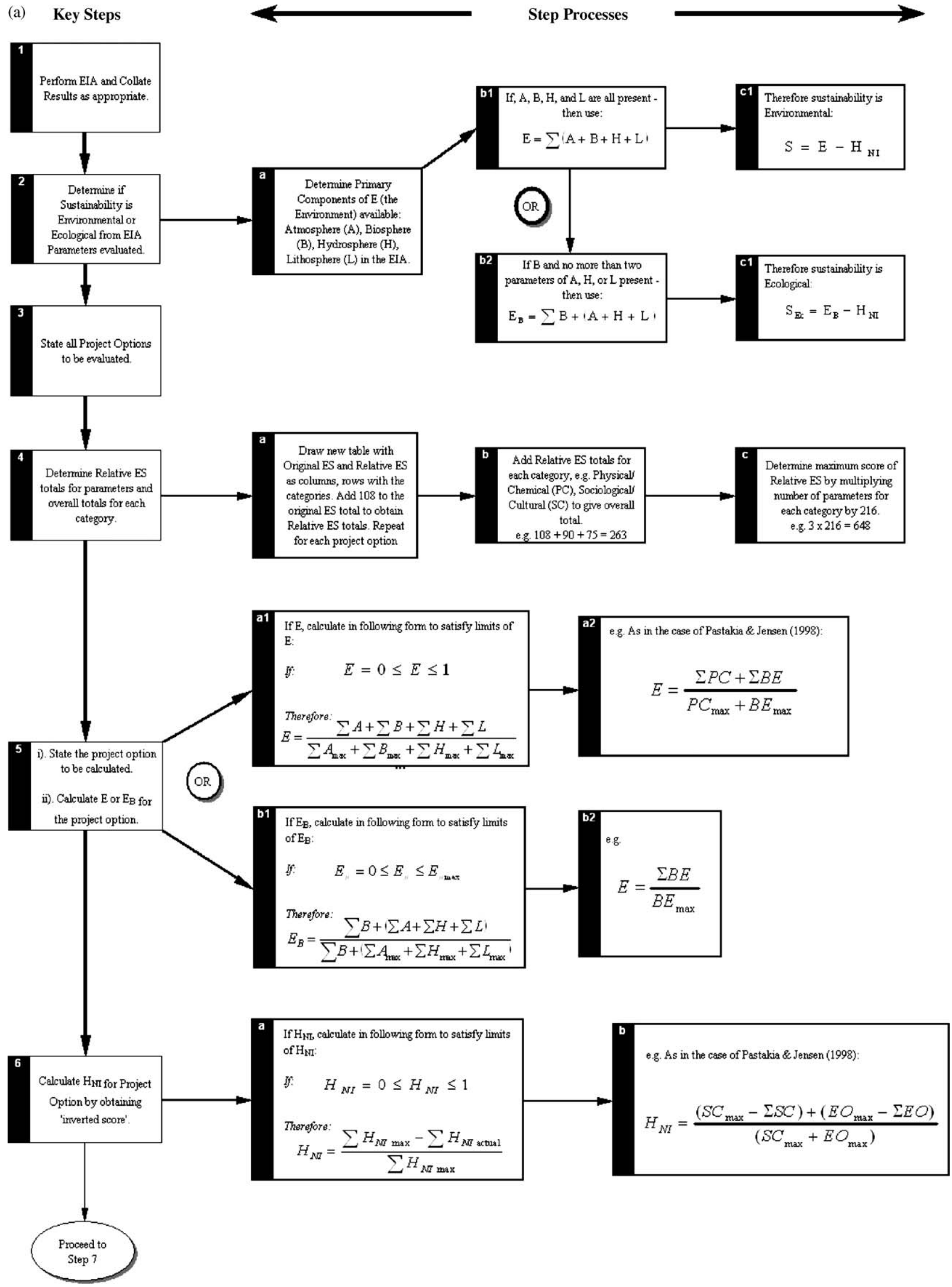

Fig. 3. The flowchart process for the application of the mathematical model of sustainable development to the Rapid Impact Assessment Matrix (RIAM) (adapted from Phillips [17,18]). (a) Outlines steps 1–6 for determining the potential type of sustainable development (environmental or ecological)[a] and the steps for calculating E or E_B and H_{NI}. (b) Outlines steps 7–11 for determining whether sustainable development is occurring, and if it is, evaluate the level and nature of sustainable development.

[a]The notion of ecologically sustainable development was introduced in respect to applying the model for two reasons, as explained by Phillips [17]: (1) The fact that ecological is often interchanged with environmental. As the model is very specific as to the definition of the environment, it was necessary to clear define what is considered as

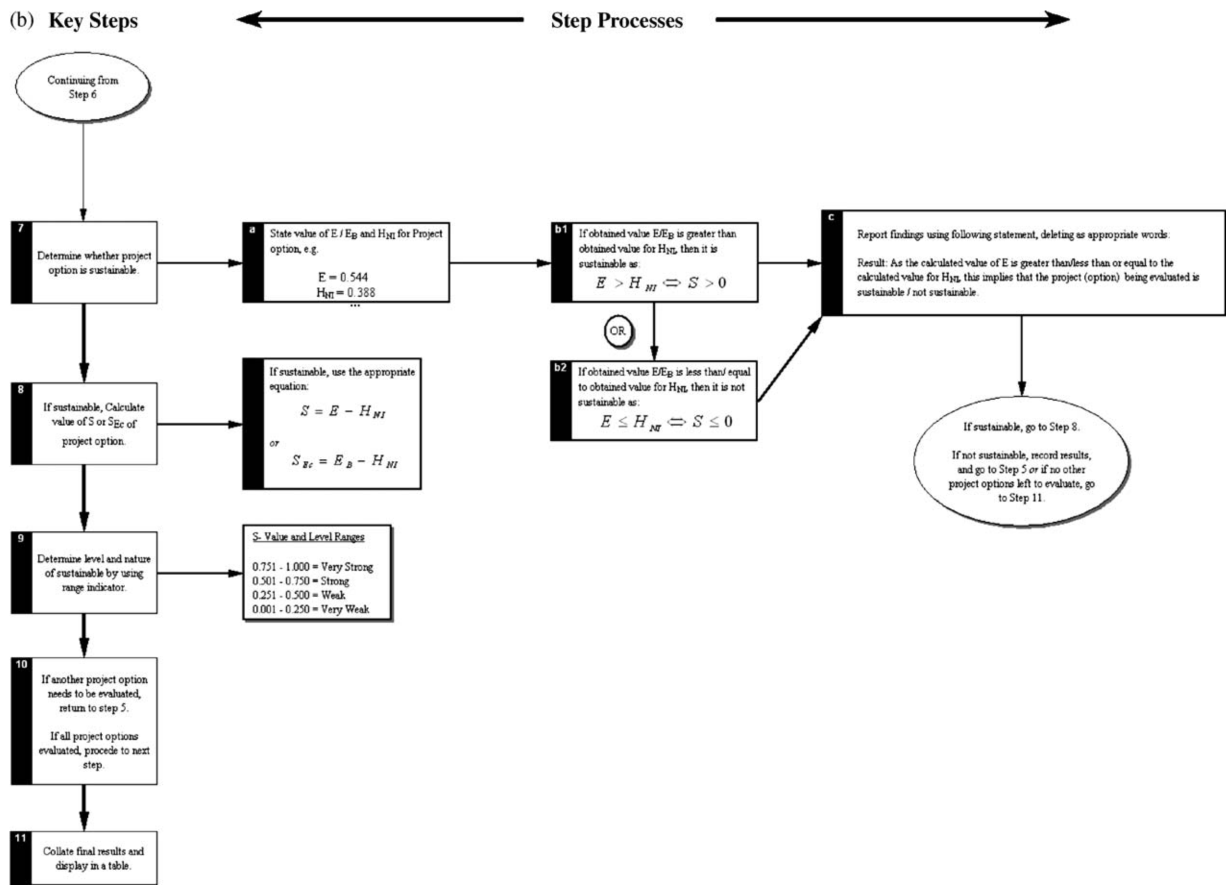

Fig. 3. (*Continued*).

4. Results: Sabalan geothermal power plant

4.1. Overview

The Sabalan geothermal power plant is planned to produce 50 MW electricity in 2011 [13]. The geothermal power plant will be located in the north-western Sabalan geothermal field in NW Iran, which is approximately 16 km SE of Meshkinshahr city [13]. The study area is Khiav River catchment and is approximately 130 km^2 [13]. After some initial interest into the potential of geothermal resources in north of Iran, more detailed investigations were undertaken into the geothermal potential of the Sabalan area in NW Iran [13]. The EIA study sought to identify and assess the likely key impacts of geothermal exploration, drilling and operation [13]. The information on was collected during 2000–2003, before starting the proposed project activities [13].

4.2. Environmental baseline data

The baseline data for the RIAM analysis of the Sabalan geothermal power plant was detailed by Yousefi et al. [13], which the following are the key environmental issues of the project:

4.2.1. Physical–chemical (PC)

- Geology
  - Sabalan is a large strato-volcano, consists of an extensive central edifice built on a probable tectonic horst of underlying intrusive and effusive volcanic rocks.
- Land Use
  - The land is mainly used to grazing and for growing crops.
  - Where the native vegetation is mostly grass or shrubs, the sheep and cattle are allowed to graze, with consequent environmental damage due to overgrazing.
  - Agricultural activities are restricted to spring and summer due to climatic conditions.
  - The development of a geothermal power project that could cover some 160 ha will reduce the amount of land available for agriculture and grazing, and increase the pressure on endemic plant communities.
- Climate
  - H_2S distribution prediction model was prepared to find the impacts on local air quality in the NW Sabalan geothermal field.
  - The results showed that there is no adverse effect of H_2S concentrations in 98% of the area and only 2% will be impacted close to the two of the wells.
  - The concentrations of H_2S in the under risk areas will be 28–31 ppb and at least once a year the concentration of H_2S will be exceed than national air quality standard (citing [34]).
- Hot springs
  - Several hot springs, with temperatures in the 20–85 °C range, exist in the study area.
  - These springs are divided into two groups according to their water chemistry:
    (a) Neutral-Cl-SO_4 springs with up to 1500 ppm of chlorides, 442 ppm of sulphates, relatively high concentrations of magnesium (up to 24 ppm), and a pH between 6.1 and 6.8.

environmental and ecological when applying the model; and (2) as EIAs tend to sometimes concentrate on ecological components as the environment, this required a clear mathematical definition in respect to applying the model to EIAs in respect to the last point.

(b) Acid-SO_4 springs with a pH of 4.3, 3.2, 3.5 and 2.8, formed by condensation and oxidation of H_2S, implying boiling at depth.

- Water quality
  - Khiav River is not only used as potable water for Meshkinshahr city, but also during the spring and summer seasons conveyed into several canals to use in agriculture and horticulture.
  - Based on the altitude of the drinking water station, which is located in the lower part of Khiav River, it is expected that the pollution from drilling activities, surface runoffs or ground water discharges can enter into the potable water supply.
- Noise
  - Noise emissions are expected to be of moderate intensity during the development and operation of geothermal facilities in the Sabalan area.
  - There is no difficulty in meeting the standard of 65 dB(A) at 0.8 km from the sources. Thus, the noise impact of power plant operations and well drilling will not be significant.
  - However, because of the low ambient noise levels, geothermal noise might be audible at distances of below 3.2 km.

4.2.2. Biological–ecological (BE)

- Flora and vegetation
  - The study area, with a mean annual precipitation of 300–450 mm, is mostly covered by steppe flora.
  - Different grasses were very common in the past, but have been greatly reduced by human activities, particularly by over-grazing.
  - Animal husbandry is the occupation of the most residents in the Sabalan area, and protection of vegetation is very important task for the developers.
- Fauna
  - The fauna is a part of a land's yield and depends on its potential and its fluctuation.
  - The region has remarkably diverse wildlife such as the wild goat, brown bear, fox, deer, wolf, partridge, rabbit, and many different species of birds and mammals.
  - Sabalan was originally a wildlife habitat. The hope is that the Sabalan geothermal project will not affect the wildlife species, especially their habitats and biodiversity.

4.2.3. Sociological–cultural (SC)

There are three villages located in the study area with agriculture as the dominant occupation. The project would require both short and long-term employment: some of them could be accommodated by the resident population without the need to import employees; and some should be imported, especially in the case of professionals and high educated, which would be a beneficial impact of the project. Settlements of educated people and communication with the native residents will bring the positive impacts in the terms of culture, education, archaeology, science, recreation and migration.

4.3. Economic–operational (EO)

- Job
  - The main occupations of the inhabitants are trading, farming, fish farming and ranching. There are no industrial activities in the area.
  - For several decades this region has suffered from brain drain especially in the case of educated people.
  - After starting the geothermal project activities, many new jobs opportunity were opened, and in some cases the people can have two jobs at the same time.
  - The developer estimated after operation commences, around 200 people will get the job in all over the field.
- Access road
  - Transportation of a drill rig, construction of buildings and installation of the plant and all the accessories and equipments requires the construction of access roads in the area.
  - After starting the project activities, the construction of a 10 km access road in the project site was already done and made the transportation easier for the residents, nomadic tribe, mountain climbers and manpower for the geothermal project.
- Tourism
  - A large number of lakes, natural marshes, mineral water springs, impressive mountains, preservations, diverse plants and wildlife, and finally its desirable honey, makes Sabalan one of the most attractive mountain regions of Iran and perhaps Asia.
  - Opening up the area by way of new roads for a project would change conditions drastically and might bring in a greatly increased number of tourists.
  - The presence of geothermal power plant development may produce a new tourist attraction in the Sabalan area, and for this reason, the natural recovery is extremely important over the vegetation and over the fauna to achieve the positive impacts.

4.4. RIAM analysis for Sabalan geothermal field

The RIAM analysis for the Sabalan geothermal field produced the following results summarised in Table 3.

Utilising the methodology illustrated in Fig. 3 for applying the mathematical model of sustainable development to the results obtained using the RIAM methodology, the results outlined in Tables 4 and 5 were obtained:

Using steps 3–6 in Fig. 3a, the following calculated values for E and H_{NI} were obtained:

$E = 0.450$

$H_{NI} = 0.387$

Thus:

$$E > H_{NI} \Leftrightarrow S > 0$$

Table 3
Summarised results of RIAM analysis for the Sabalan geothermal field, adapted from Yousefi et al. [13].

	Components	ES	RB
PC1	Air quality	−12	−B
PC2	Noise	−12	−B
PC3	Groundwater	−14	−B
PC4	Surface water	−12	−B
PC5	Land use	−10	−B
PC6	Subsidence	−7	−A
PC7	Visual impacts	3	+A
PC8	Soil pollution	−18	−B
BE1	Fauna	−12	−B
BE2	Flora	−12	−B
BE3	Vegetation	−20	−C
BE4	Habitat loss	−3	−A
SC1	Culture	14	+B
SC2	Education	28	+D
SC3	Archaeology	3	+A
SC4	Science	35	+D
SC5	Recreations	−6	−A
SC6	Migration	20	+C
EO1	Jobs	45	+D
EO2	Access road	30	+C
EO3	Public services	54	+D
EO4	Tourism	54	+D
EO5	Land prices	18	+B
EO6	Agriculture	−15	−B
EO7	Transportation	36	+B

Table 4
A table indicating the results for the calculation of the relative ES necessary to apply the mathematical model of sustainable development to the results obtained using the RIAM methodology for the Sabalan geothermal power plant, with reference to Table 3.

	Components	ES	Relative ES
PC1	Air quality	−12	96
PC2	Noise	−12	96
PC3	Groundwater	−14	94
PC4	Surface water	−12	96
PC5	Land use	−10	98
PC6	Subsidence	−7	101
PC7	Visual impacts	3	111
PC8	Soil pollution	−18	90
		ΣPC	782
BE1	Fauna	−12	96
BE2	Flora	−12	96
BE3	Vegetation	−20	88
BE4	Habitat loss	−3	105
		ΣBE	385
SC1	Culture	14	122
SC2	Education	28	136
SC3	Archaeology	3	111
SC4	Science	35	143
SC5	Recreations	−6	102
SC6	Migration	20	128
		ΣSC	742
EO1	Jobs	45	153
EO2	Access road	30	138
EO3	Public services	54	162
EO4	Tourism	54	162
EO5	Land prices	18	126
EO6	Agriculture	−15	93
EO7	Transportation	36	144
		ΣEO	978

Table 5
A summary table of the relative ES totals and potential maximum scores for each category for the Sabalan geothermal power plant.

Components	Totals
ΣPC	728
PC_{max}	1728
ΣBE	385
BE_{max}	864
ΣSC	742
SC_{max}	1296
ΣEO	978
EO_{max}	1512

4.4.1. Result

As the calculated value of E is greater than to the calculated value for H_{NI}, this implies that the project option being evaluated is environmentally sustainable.

Consequently:

$$S = E - H_{NI}$$

$$S = 0.450 - 0.387$$

$$S = 0.063$$

Using the table in step 9 in Fig. 3b, the value of S obtained infers that sustainable development is considered to be very weak.

5. Discussion

5.1. Results of model application

The results show that a value of $S = 0.063$ was obtained for the level of sustainable development of the proposed Sabalan geothermal power plant. This would indicate that the nature of sustainable development is considered as very weak. However in point of fact, it could be described as barely sustainable. This result certainly somewhat surprising given the fundamental belief that geothermal is a component necessary to achieve sustainable development in respect to energy production. Consequently, the question becomes why this may be the case?

The primary reason would appear to be that the suggested positive impacts of the socio-economic factors (SC and EO components) tend to greatly outweigh the inferred negative impacts of the environmental factors (PC and BE components). This would infer that there would be improved socio-economic quality of life of the local inhabitants, but at the expense of the environmental quality of the area. This may create the basis for potential severe changes that may alter the current balance within the clearly fragile local Earth system, as highlighted by the RIAM results obtained by Yousefi et al. [13]. This is supported by the fact that many of the PC and BE components have changes that are deemed to be generally negative in nature, with reference to Table 2.

Consequently, the imbalance between the environmental and anthropogenic aspects of the project is the key issue of concern, particularly in respect to the sustainable development basis of the project. The S-value infers as much, due to the poor result obtained for a supposedly sustainable project. The results outlined in Table 3 suggest that the local environment could be altered enough to be significant in degrading quality of life of the local area. This may further impact the present economy based on tourism, culture and agriculture.

There are further two potential issues of concern in respect to the context of the results obtained by Yousefi et al. [13]:

(1) The potential issues as to environmental impacts of geothermal power plants are well documented in the literature. The fact that no management or mitigation scenarios were evaluated as part of the EIA, this could be considered as a significant drawback, and potentially evidence of poor practice. The failure to properly develop and assess potential management plan(s) as well as different scenarios/alternatives as part of the RIAM analysis would seem to suggest a hasty and pre-judged process for implementation. This may have been done with little consideration for potential costs to the existing conditions of the local area—environmental, economic and social.

(2) Yousefi et al. [13] tends to infer that the results are generally positive in favour of the project. Yousefi et al. [13] states that the RIAM analysis indicated that 57% of the components were positive, whilst 43% were negative due to residual impacts from the project. However, the significant majority of negative impacts were environmental in nature; and the positive impacts were predominantly socio-economic in nature. This, from a sustainability science perspective, would appear to be the continuation of the flawed rationale of the Brundtland/WCED definition[1] of an anthropogenic-centred sustainable development. This contrary to the development of a co-evolutionary relationship between the environment and humans necessary for achieving sustainable development.

The evaluation of sustainable development using the model infers that the project, from a sustainability science perspective,

[1] Development that meets the needs of the present without compromising the ability of future generations to meet their own needs [36].

requires substantive improvements to minimise and management of the environmental impacts, even if it results in some reduction to the economic and social factors. The results further suggests that the disruption to pre-existing economic activities of the area may create further pressures to modes of agriculture and any existing management of the local environment. Whilst, the improvement to economic and social quality of life may be very much welcome, the disruption of environmental and cultural quality may not be as welcome. This is due to the inherent cultural and religious values within Iran, as well as the constitutional requirement to prevent environmental pollution or irreversible damage, as noted by Yousefi et al. [13]. This requirement would seem not to be wholly reflected in the results obtained in the EIA conducted, and somewhat in respect to the evaluation of *S*. The fact that whilst the impacts may not be of significance and local in magnitude, they are nevertheless still negative and permanent in nature as long as the plant operates. This would consequently mean that the Sabalan geothermal power plant would be apparently in conflict to the constitution of Iran.

In summary, whilst the project is deemed to be sustainable, it is considered to be very weak in nature. This would infer that substantial improvements and management to the environmental aspects are required. This should increase the value obtained for *E*, and thus improve the *S*-value as well.

5.2. Potential implications

The results obtained for the model application were surprising, given the very low value of *S*, and the backdrop of the strong perception of its contribution towards sustainable development. The inference of the negative environmental impacts in comparison to positive socio-economic impacts would very much appear to be in conflict to the ideals of sustainable development. Such results as those obtained for Sabalan, as a single case study, may be considered as an anomaly. However, when compared and contracted to the RIAM analysis results obtained for the Tuzla geothermal power plant in Turkey (see [35]), then a different outcome begins to emerge. The results obtained for the Tuzla geothermal power plant are outlined in Table 6.

By utilising steps 3–9 outlined in Fig. 3, Tables 7 and 8 were obtained and a *S*-value of 0.078 was calculated for the Tuzla geothermal power plant. This S-value indicates sustainable development that is very weak in nature.

The similar disparity in the environment and anthropogenic values obtained in the RIAM analysis of Tuzla, in regards to a similar very low value of *S* is evident, as with Sabalan. This result obtained would appear to be of some considerable interest. If placed in the context of the following factors: the independence of the results obtained; and the different locations, environment and socio-economic characteristics—then the similarities contained in both sets of results, in respect to Sabalan and Tuzla, would appear to be of some significance.

The results would certainly appear to raise some legimate questions as to the environmental credentials of geothermal power production. However, perhaps most critically of all, it raises potential questions in regards to the sustainable development aspects. Specifically, does geothermal energy provides an effective alternative as a non-polluting source of energy which contributes to economic growth, and thus sustainable development? With respect to the results presented in this paper, then it would certainly appear that geothermal energy is in some doubt with respect to this question.

The evident imbalance between the environmental and anthropogenic components implies that sustainable development is, in the case of geothermal energy, still predominantly anthropogenic in nature. The notion or concept of a fully functioning environment to maintain the local and broader Earth system, is still not taken into account, even in the case of projects which promote perceived environmentally friendly energy production. Consequently, geothermal energy may not at present be a viable long-term option, unless there is more stringent management and mitigation of the environmental and pollution aspects in respect to electricity production, particularly in developing countries eager to pursue

Table 6
Summarised results of RIAM analysis for the Tuzla geothermal field, adapted from Baba [35].

	Components	ES	RB
PC1	Land use changes	−10	−B
PC2	Noise	−12	−B
PC3	Surface water	−12	B
PC4	Air	−18	−B
PC5	Landscape	3	A
PC6	Geology	0	N
PC7	Agriculture	−18	−B
PC8	Groundwater	−14	−B
BE1	Vegetation	−12	−B
BE2	Fauna	−12	−B
BE3	Flora	−12	−B
BE4	Habitat loss	0	N
BE5	Recreation	3	A
SC1	Cultural	14	B
SC2	Natural protection	−12	−B
SC3	Archaeological	18	B
SC4	Science	42	D
SC5	Education	7	A
EO1	Transport	28	C
EO2	Services	42	D
EO3	Work	21	C
EO4	Tourism opportunity	42	D
EO5	Access road improvement	28	C
EO6	Employment opportunity	42	D

Table 7
A table indicating the results for the calculation of the relative ES necessary to apply the mathematical model of sustainable development to the results obtained using the RIAM methodology for the Tuzla geothermal field, with reference to Table 6.

	Components	ES	Relative ES
PC1	Land use changes	−10	98
PC2	Noise	−12	96
PC3	Surface water	−12	96
PC4	Air	−18	90
PC5	Landscape	3	111
PC6	Geology	0	108
PC7	Agriculture	−18	90
PC8	Groundwater	−14	94
		ΣPC	783
BE1	Vegetation	−12	96
BE2	Fauna	−12	96
BE3	Flora	−12	96
BE4	Habitat loss	0	108
BE5	Recreation	3	111
		ΣBE	507
SC1	Cultural	14	122
SC2	Natural protection	−12	96
SC3	Archaeological	18	126
SC4	Science	42	150
SC5	Education	7	115
		ΣSC	609
EO1	Transport	28	136
EO2	Services	42	150
EO3	Work	21	129
EO4	Tourism opportunity	42	150
EO5	Access road improvement	28	136
EO6	Employment opportunity	42	150
		ΣEO	851

Table 8
A summary table of the relative ES totals and potential maximum scores for each category for the Tuzla geothermal field.

Components	Totals
ΣPC	783
PC_{max}	1728
ΣBE	507
BE_{max}	1080
ΣSC	609
SC_{max}	1080
ΣEO	851
EO_{max}	1296

this form of energy production, i.e. Turkey and Iran. If improved environmental management was incorporated within the operational design, then this may improve the calculated value of *S* if the RIAM analysis is repeated. However, given the environmental sensitivity of Sabalan, as well as Tuzla, this may only improve the *S*-value of the project(s) to be considered as weak in nature.

6. Conclusion

This paper has indicated that geothermal power production, whilst it could be considered as sustainable, it is very weak in nature given the negative environmental impacts created. Therefore, it is certainly relevant and appropriate that further research is conducted in order to determine potential mechanisms for improving the environmental aspects related to geothermal power production, and the overriding sustainable development considerations. Perhaps more importantly is the fact that this paper has provided a calculated value of the level of sustainable development and determined its nature in respect to renewable energy production plant through the EIA conducted for the Sabalan and Tuzla operations. This is a potential improvement on purely subjective evaluations of the sustainable development aspects of a project. It offers a more considered approach to determining sustainable development, and for making appropriate adjustments to project in order to improve the sustainability of them. Consequently, it is hoped this paper be a conduit and a contribution towards the pursuit of sustainable sources of energy, now and in the future.

References

[1] Marchetti C. From principles to world government. Laxenburg, Austria: International Institute for Applied Systems Analysis; 1995.
[2] Bilen K, Ozyurt O, Bakirci K, et al. Energy production, consumption, and environmental pollution for sustainable development: A case study in Turkey. Renewable and Sustainable Energy Reviews 2008;8:1529–61.
[3] Yuksel I. Global warming and renewable energy sources for sustainable development in Turkey. Renewable Energy 2008;33:802–12.
[4] Erdogdu E. A snapshot of geothermal energy potential and utilization in Turkey. Renewable and Sustainable Energy Reviews 2009;13:2535–43.
[5] Komurcu MI, Akpinar A. Importance of geothermal energy and its environmental effects in Turkey. Renewable Energy 2009;34:1611–5.
[6] Murphy S H., Niitsuma S H.. Strategies for compensating for higher costs of geothermal electricity with environmental benefits. Geothermics 1999;28: 693–711.
[7] Lowe P, Murdoch J. Rural sustainable development. Rural development commission—strategy review: topic paper 1. London: Rural Development Commission; 1993.
[8] Afgan NH, Al Gobashi D, Carvalho MG, Cumo M. Sustainable energy development. Renewable and Sustainable Energy Review 1998;2:235–86.
[9] Kaygusuz K, Kaygusuz A. Renewable energy and sustainable development. Renewable Energy 2002;25(2002):431–53.
[10] Hepbasil A. A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renewable and Sustainable Energy Reviews 2008;12:593–661.
[11] Omer AM. Energy, environment and sustainable development. Renewable and Sustainable Energy Reviews 2008;12:2265–300.
[12] Reddy AKN. Energy for sustainable development, vol. 6, no. 3; September 2002.
[13] Yousefi H, Ehara S, Yousefi A, Seiedi F. Environmental impact assessment of Sabalan geothermal power plant, NW Iran. Proceedings of the 34th workshop on geothermal reservoir engineering. Stanford, California: Stanford University; 9–11 February 2009. Accessed from: http://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2009/yousefi.pdf [13th January 2009].
[14] Brophy P. Environmental advantages to the utilization of geothermal energy. Renewable Energy 1997;10(2/3):367–77.
[15] Pastakia CMR. The Rapid Impact Assessment Matrix (RIAM)—a new tool for environmental impact assessment; 1998. Accessed from: http://www.pastakia.com/riam/publication.html [03.06.2006].
[16] Pastakia CMR, Jensen A. The Rapid Impact Assessment Matrix (RIAM) for EIA. Environmental Impact Assessment Review 1998;18:461–82.
[17] Phillips J. The development and application of a geocybernetic model of sustainability. PhD thesis (unpublished). United Kingdom: Dept. of Geography (Streatham Campus) and Camborne School of Mines (Cornwall Campus), University of Exeter; 2009.
[18] Phillips J. The advancement of a mathematical model of sustainable development. Sustainability Science 2010;5(1):127–42. doi:10.1007/s11625-009-0103-3.
[19] Dee N, Baker JK, Drobny NL, et al. An Environmental Evaluation System for Water Resource Planning. Water Resources Research 1973;9(3):523–35.
[20] Taleb HM. Barriers hindering the utilisation of geothermal resources in Saudi Arabia. Energy for Sustainable Development 2009;13:183–8.
[21] Lund J. 100 years of renewable electricity-geothermal power production. Renewable Energy World 2005;8(5):252–9.
[22] Sawin J. Mainstreaming renewable energy in the 21st century. Worldwatch Paper 169. Washington, DC: Worldwatch Institute; 2004.
[23] Hepbasil A, Ozgener L. Development of geothermal energy utilization in Turkey: a review. Renewable and Sustainable Energy Reviews 2004;8: 433–60.
[24] Barbier E. Geothermal energy technology and current status: an overview. Renewable and Sustainable Energy Reviews 2002;6:3–65.
[25] Fridleifsson IB. Geothermal energy for the benefit of the people. Renewable and Sustainable Energy Reviews 2001;5:299–312.
[26] Layton DW, Anspaugh LR, O'Banion KD. Health and environmental effects, document on geothermal energy. Report UCRL-53232. Livermore, CA, USA: Lawrence Livermore Laboratory; 1981
[27] Pasqualetti MJ. Geothermal energy and the environment: the global experience. Energy 1980;5:111–65.
[28] World Summit on Sustainable Development (WSSD). Plan of implementation of the World Summit on sustainable development. New York: United Nations; 2002. Accessed from: www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/WSSD_PlanImpl.pdf [13th January 2006].
[29] Clark WC. Sustainability science: a room of its own. Proceedings of the National Academy of Sciences of the United States of America (PNAS) 2007;104(6):1737–8.
[30] Kates RW, Clark WC, Corell R, et al. Sustainability science. Science 2001;292:641–2.
[31] Clark WC, Crutzen PJ, Schellnhuber H-J. Science for global sustainability: toward a new paradigm. CID working paper no. 120. Harvard University Center for International Development; March 2005.
[32] Stokes DE. Pasteur's quadrant: basic science and technological innovation. Washington, DC: Brookings Institution; 1997.
[33] El-Naqa A. Environmental impact assessment using rapid impact assessment matrix (RIAM) for Russeifa landfill, Jordan. Environmental Geology 2005;47: 632–9.
[34] Yousefi H, Ehara S, Noorollahi Y. Air quality impact assessment of Sabalan geothermal power plant project NW Iran. Proceedings of the 33rd workshop on geothermal reservoir engineering. Stanford, California: Stanford University; 2008. p. 216–22.
[35] Baba A. Geothermal environmental impact assessment with special reference to the Tuzla, geothermal area, Canakkale, Turkey. Reykjavik, Iceland: Geothermal Training Programme, The United Nations University; 2003. Accessed from: www.unugtp.is/solofile/1421]3rd November 2009].
[36] World Commission on Environment and Development (WCED). Our common future. Oxford: Oxford University Press; 1987.